Introduction to Particle Physics
- Chapter 9 -
CP violation in the B^0 system

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Chapter summary:

- Mixing in the neutral mesons
- Mixing in the B^0 mesons
- CKM matrix and CP violation
- CP violation in the B^0 mesons
- Pep II asymmetric B-factory at SLAC
- Quantum entanglement in the $B^0\bar{B}^0$ system
- Measurement of the CP violation in the B^0 mesons
- Direct CP violation in the B^0 mesons

Is CP violated only in the K^0 system?

- In1964 was discovered the CP violation in the mixing of the neutral K system (people were invoking a superweak interaction that intervenes in the transitions with $\Delta S=2$).
- The direct CP violation (with $\Delta S=1$) was experimentally verified more than 30 years later.
- In 1973 Kobayashi and Maskawa made the hypothesis of the existence of 3 quark families in order to accomodate a phase in the quark mixing matrix that would be responsible of the CP violation in the weak interactions.
- In 1974 was discovered the quark c and in 1977 the quark b
- In the 80s start the search for the quark mixing in the B^0 system.
- In the late 90s start the search of the CP violation in the B^0 system.

Mixing of the neutral mesons

- Besides the K^0, other neutral mesons can "mix".

	u	c	t
$\overline{u}$	$\times$	D^0	$\diamond$
$\overline{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\overline{t}$	$\diamond$	$\diamond$	$\times$

	d	s	b
$\overline{d}$	$\times$	K^0	B^0
$\overline{s}$	$\overline{K^0}$	$\times$	B_s
$\overline{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

- Need to be neutral and have distinct anti-particle (x)
- Needs to have a non-zero lifetime
  - top is so heavy, it decays long before it can even form a meson ($\diamond$)
- That leaves four distinct cases...

B mesons

Symbol	Quark	isospin	Mass (GeV)	S	C	B	Lifetime (s)
B^+	$u\bar{b}$	½	5.279	0	0	1	1.64×10^{-12}
B^0	$d\bar{b}$	½	5.279	0	0	1	1.52×10^{-12}
B^0_S	$s\bar{b}$	0	5.366	-1	0	1	1.51×10^{-12}
B^+_C	$c\bar{b}$	0	6.275	0	1	1	0.51×10^{-12}

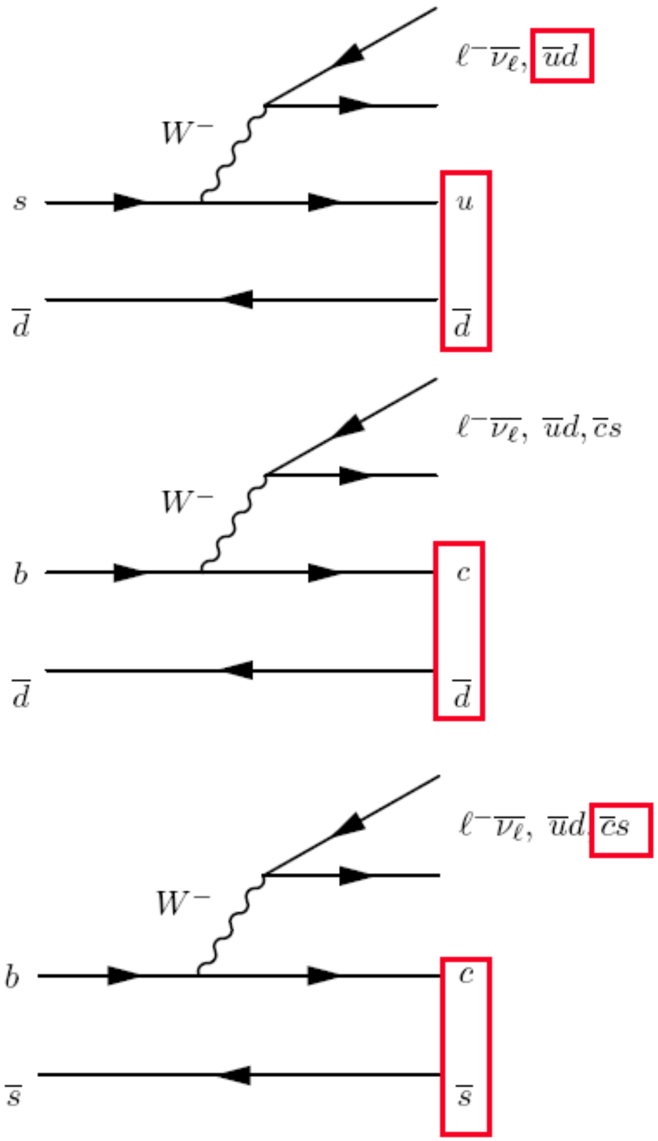
Mixing: Kaons versus B mesons

- The difference between K mixing and 'the rest': Γ_{12}

$$\Gamma_{12} = \Gamma_1 - \Gamma_2$$

- A *large* fraction of Kaon decays produce CP eigenstates:
  - all decays *without* leptons are CP eigenstates..
- the CP even ones have more phase-space
  - Hence the lifetime difference (large Γ_{12}!)

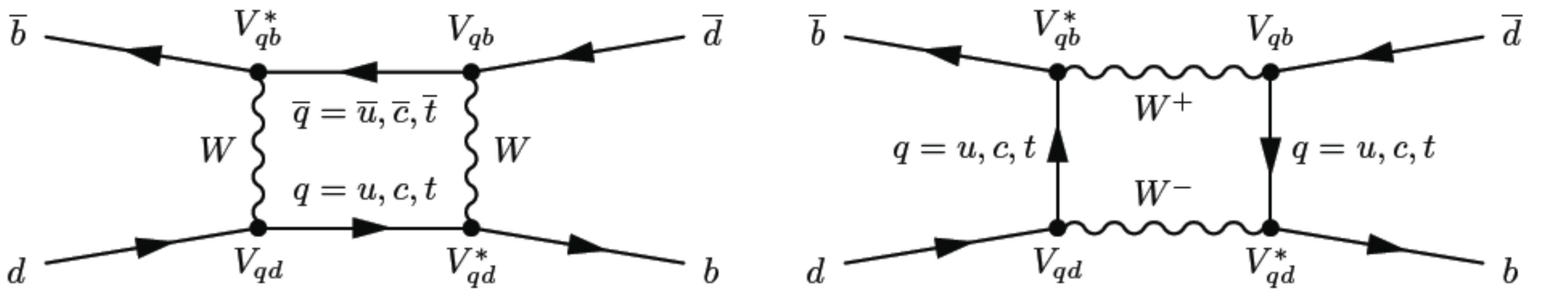
- For B^0, (and, to a somewhat lesser extent, B_s), the dominant decays are *not* CP eigenstates
  - hence $\Delta\Gamma$=0 (smallish), and Γ_{12} does *not* contribute to B^0 mixing
  - note: as a result labeling eigenstates as 'S'hort and 'L'ong doesn't make sense -- hence the 'H'eavy and 'L'ight



Dominant decay amplitudes

Mixing: box diagrams

N.B. We get the coupling in every vertex through the CKM matrix elements



$t-\bar{t}: \quad \propto m_t^2 \left|V_{tb}V_{td}^*\right|^2 \quad \propto m_t^2\lambda^6$

$c-\bar{c}: \quad \propto m_c^2 \left|V_{cb}V_{cd}^*\right|^2 \quad \propto m_c^2\lambda^6$

$c-\bar{t}, \bar{c}-t: \quad \propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^* \propto m_c m_t \lambda^6$

$\lambda = \sin\theta_C$

GIM(V_{CKM} unitarity):
if u,c,t same mass, everything cancels *by construction*!

Dominated by top quark mass: $\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1}$

reference: $\tau_B \sim 1.5$ ps

B^0 mixing: Argus, 1987

- Produce an $b\bar{b}$ bound state, $\Upsilon(4S)$, in e^+e^- collisions:
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B^0}$
- and then observe:

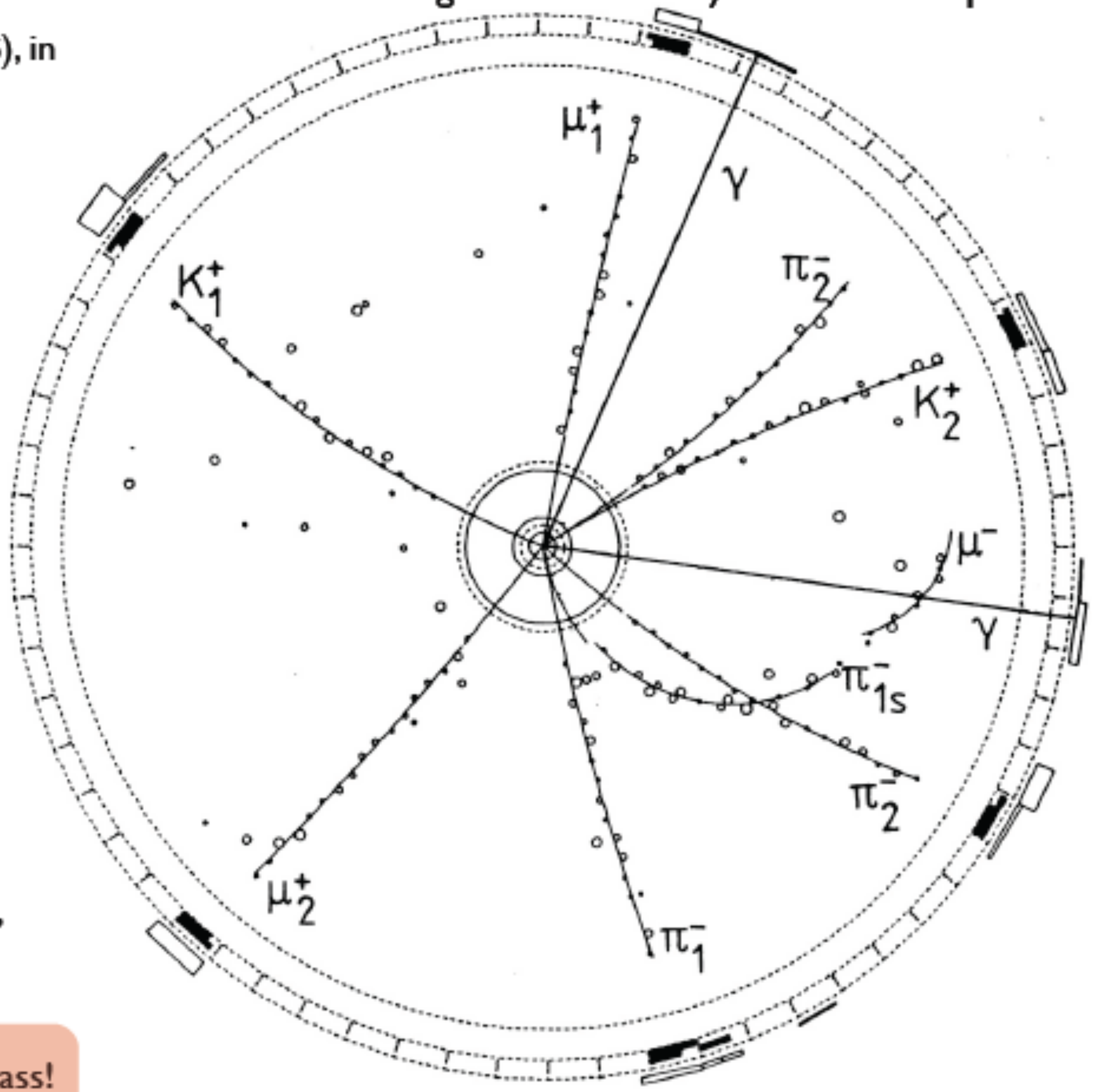
$$B_1^0 \rightarrow D_1^{*-}\mu_1^+\nu_1$$
$$D_1^{*-} \rightarrow \overline{D^0}\pi_{1s}^-$$
$$\overline{D^0} \rightarrow K_1^+\pi_1^-$$

$$B_2^0 \rightarrow D_2^{*-}\mu_2^+\nu_2$$
$$D_2^{*-} \rightarrow D^-\pi^0$$
$$D^- \rightarrow K_2^+\pi_2^-\pi_2^-$$
$$\pi^0 \rightarrow \gamma\gamma$$

- measure that ~17% of B^0 and $\overline{B^0}$ mesons oscillate before they decay
  - $\tau_B \sim 1.5$ ps $\Rightarrow$ $\Delta m_d \sim 0.5$/ps,

First evidence of a really large top mass!

Integrated luminosity 1983-87: 103 pb^{-1}



CKM matrix and CP violation

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Weak interactions eigenstates are not equal to strong interactions eigenstates

- Let's write the CKM matrix in the Wolfstein formulation, useful to describe the CP violation in the B system (there is a phase only between the third and the first family):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \overbrace{A\lambda^3(\rho - i\eta)}^{V_{ub}} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \underbrace{A\lambda^3(1-\rho - i\eta)}_{V_{td}} & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} + O(\lambda^4)$$

$\lambda = \sin\theta_c$

V_{td} and V_{ub} provide the weak phase necessary to have CP violation in the B mesons decays.

Unitarity of the matrix: $V^{\dagger}V=1$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$
$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

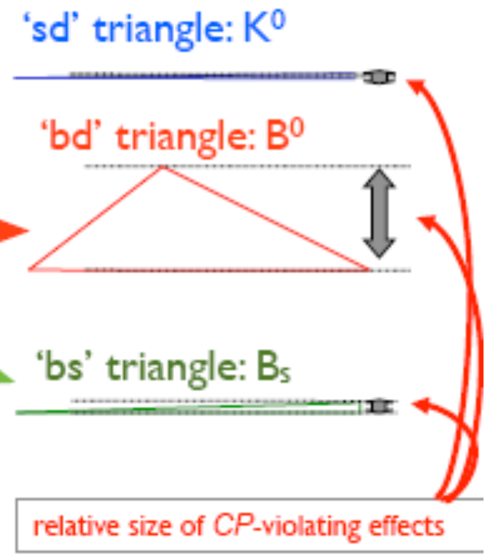
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The 6 complex "**Unitarity Triangles**" involve different physics processes

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0 \qquad \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \qquad \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0$$

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0 \qquad \mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0$$



$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

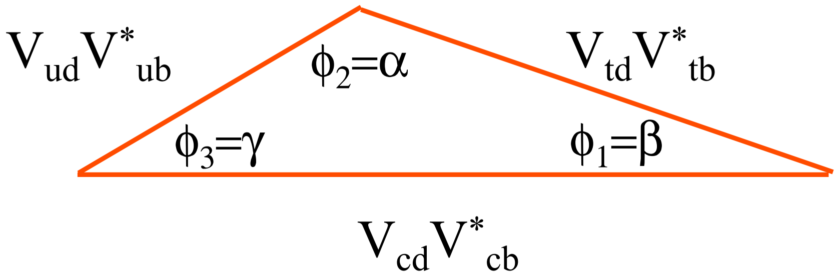
$$V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0$$

$$V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0$$

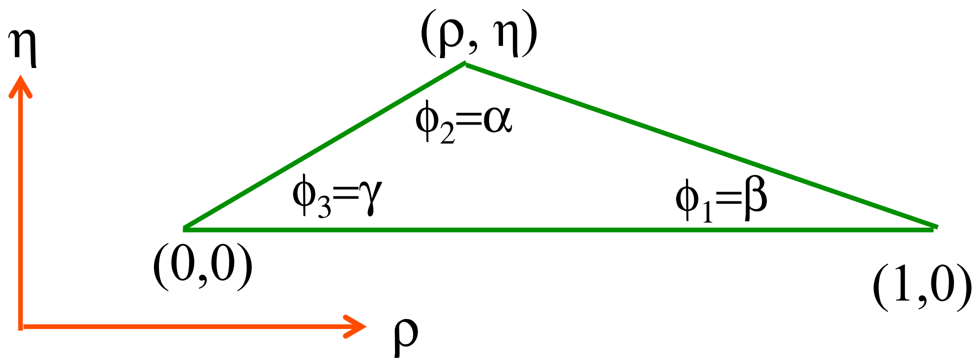
These relations can be represented as a triangle in a complex plane

Unitarity triangle

- Let's take the triangle involving B_d mesons: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$



It is convenient to normalize all unitarity triangle sides to the base of the triangle ($V_{cd}V^*_{cb} = A\lambda^3$). In the plane ($\rho$,$\eta$) the triangle becomes:



Another way to verify the CP violation in the B system is to verify that the area of this triangle is different from zero.

For instance by measuring the angle β

By measuring in an independent way all sides and angles of the triangles, we can check experimentally if the trangle "closes". If this were not the case then it would be the evidence of new physics not foreseen by the Standard Model.

How to measure CP violation in the B^0?

- Let's recall the technique that was used to measure the CP violation in the K^0 system:

1. We get a pure K_2 beam (this is possible due to huge difference in lifetime between the two CP K_1 and K_2, so we only need a long decay tunnel to get rid of the K_1 component)
2. We look for K_2 decays in the "wrong" CP eigenstate.

- The same technique can not be used to study CP violation in the B^0 system, because the lifetime of the two CP eigenstates is about the same; so there no way to separate the two components "by waiting long enough".

- So we need another "trick". CP violation is due to a phase in the CKM matrix and the only way to measure a phase is through an interference phenomenon. We need to find observables that are sensitive to the CP violating phase.

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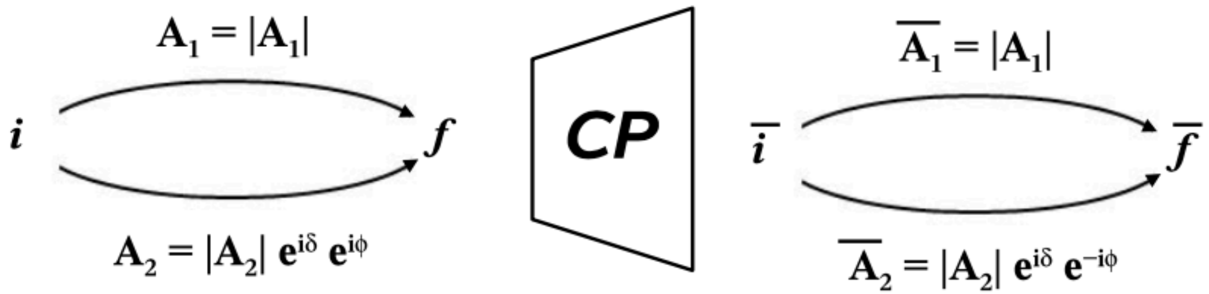
CP violation in the B^0 mesons

- We have three mechanism that can give rise to CP violation in the B0 system:
  1. CP violation purely in mixing:

$$|B_H\rangle = p|B\rangle + q|\overline{B}\rangle \qquad |B_L\rangle = p|B\rangle - q|\overline{B}\rangle \qquad \text{if } \left|\frac{p}{q}\right| \neq 1 \;\Rightarrow\; \text{CP is violated in mixing}$$

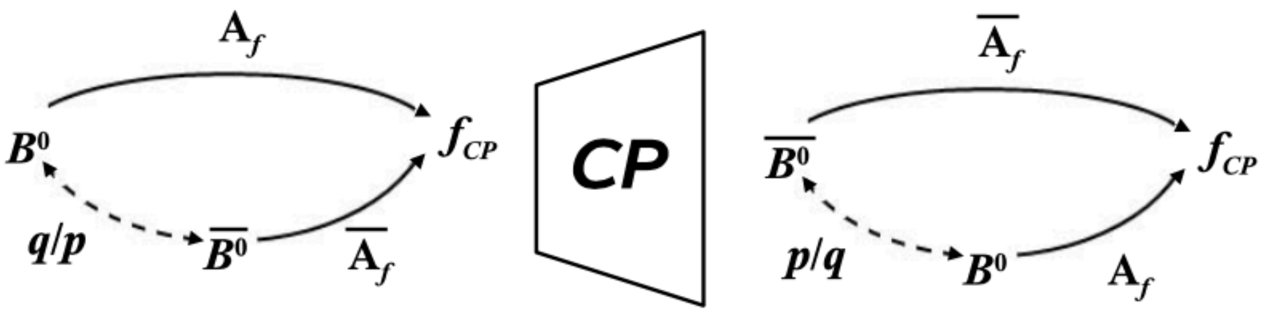
this is the main effect in the K^0 system but it is expected to be very small in the B decays

  2. CP violation in decay (often referred to as direct CP violation)



$$\left|\frac{A_f}{\overline{A}_{\bar{f}}}\right| \neq 1 \;\Rightarrow\; \text{CP is viol.}$$

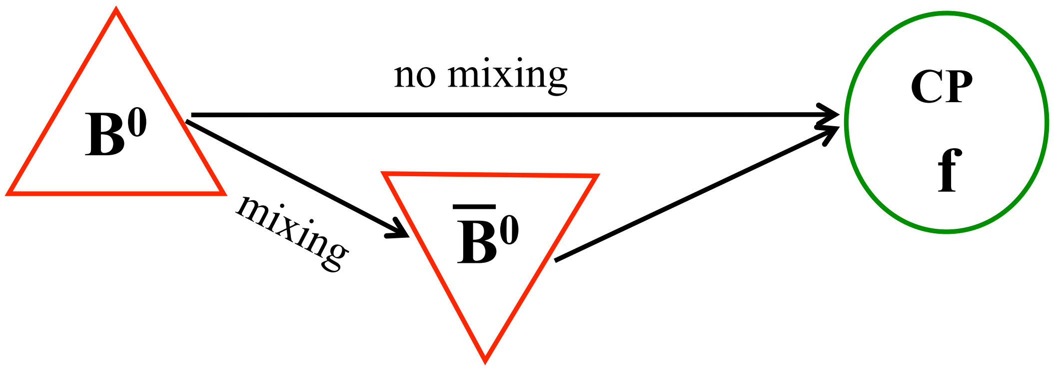
  3. CP violation in the interference between decays of mixed and unmixed mesons.



CP violation in the interference

- In order to measure the phase difference we use as interference phenomenon the B^0 decay in a final state f that is a CP eigenstate, that can proceed through two channels:

  - the direct decay of B^0 in the state f;
  - first the mixing B^0–anti B^0, then the decay of the anti B^0 in the state f:



- In this case the two amplitudes do interfere with each other;
- N.B. we can also have direct CP violation if the two decay amplitudes of the B^0 and of the anti-B^0 in the same state f are different.

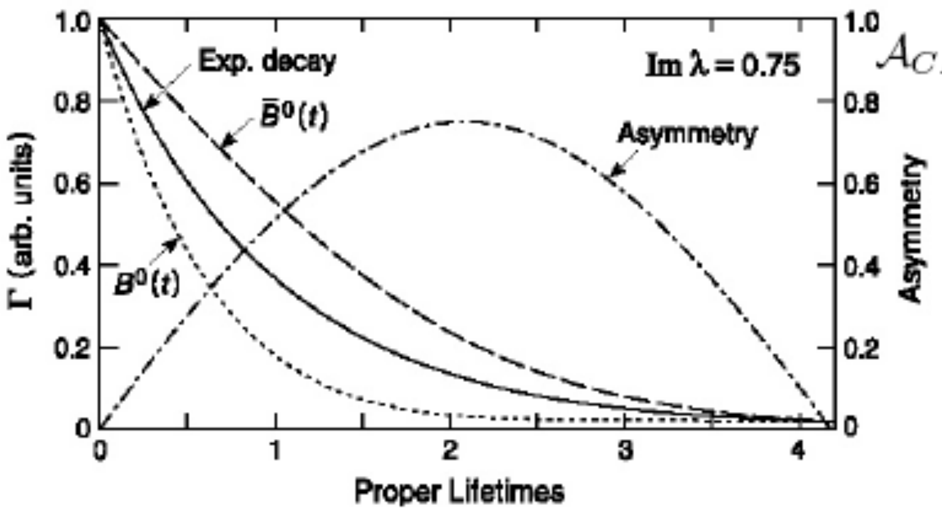
CP violation in the interference

$$|B_H\rangle = p|B\rangle + q|\bar{B}\rangle$$
$$|B_L\rangle = p|B\rangle - q|\bar{B}\rangle$$

$$\Delta m = m_{B_H} - m_{B_L}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

$t=0$	t	Rate
B^0 →	f_{CP}	$\frac{1}{2}e^{-\Gamma t}\left[1 + \left(\frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}\right)\cos(\Delta m t) - \left(\frac{2\mathcal{I}(\lambda)}{1+\lvert\lambda\rvert^2}\right)\sin(\Delta m t)\right]$
$\overline{B^0}$ →	f_{CP}	$\frac{1}{2}e^{-\Gamma t}\left[1 - \left(\frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}\right)\cos(\Delta m t) + \left(\frac{2\mathcal{I}(\lambda)}{1+\lvert\lambda\rvert^2}\right)\sin(\Delta m t)\right]$



$$A_{CP} \equiv \frac{\Gamma(\overline{B^0}\to f_{CP}) - \Gamma(B^0\to f_{CP})}{\Gamma(\overline{B^0}\to f_{CP}) + \Gamma(B^0\to f_{CP})}$$
$$= -C_{f_{CP}}\cos(\Delta m t) + S_{f_{CP}}\sin(\Delta m t)$$

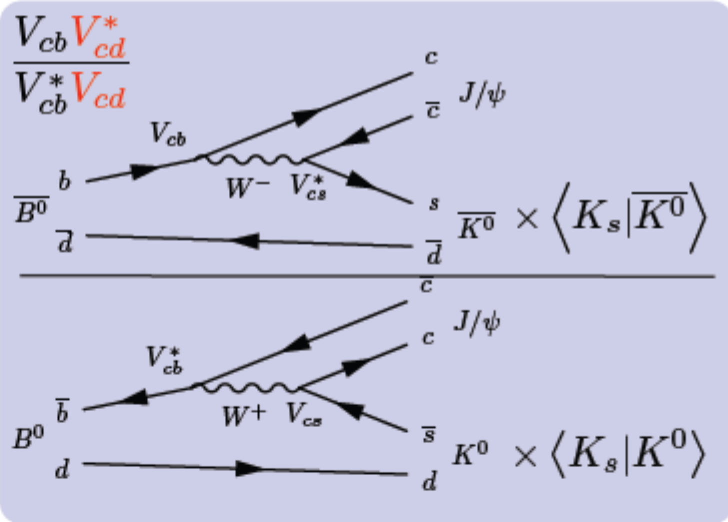
↑ CP in decay

↑ CP in interference between decay and mixing

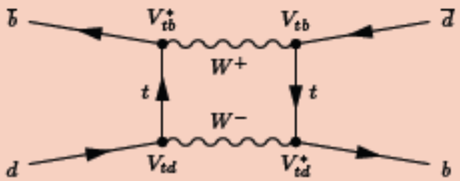
Next: find the right state f_{CP}

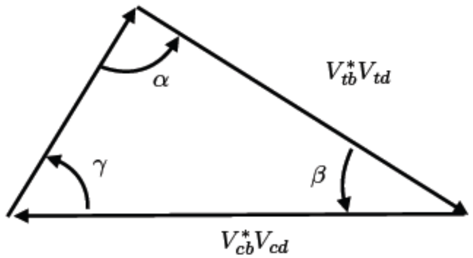
Golden channel: B→ J/Ψ Ks

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0},\overline{K^0}\to K_S}}{A_{J/\psi K^0,K^0\to K_S}}$$



$$\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}$$

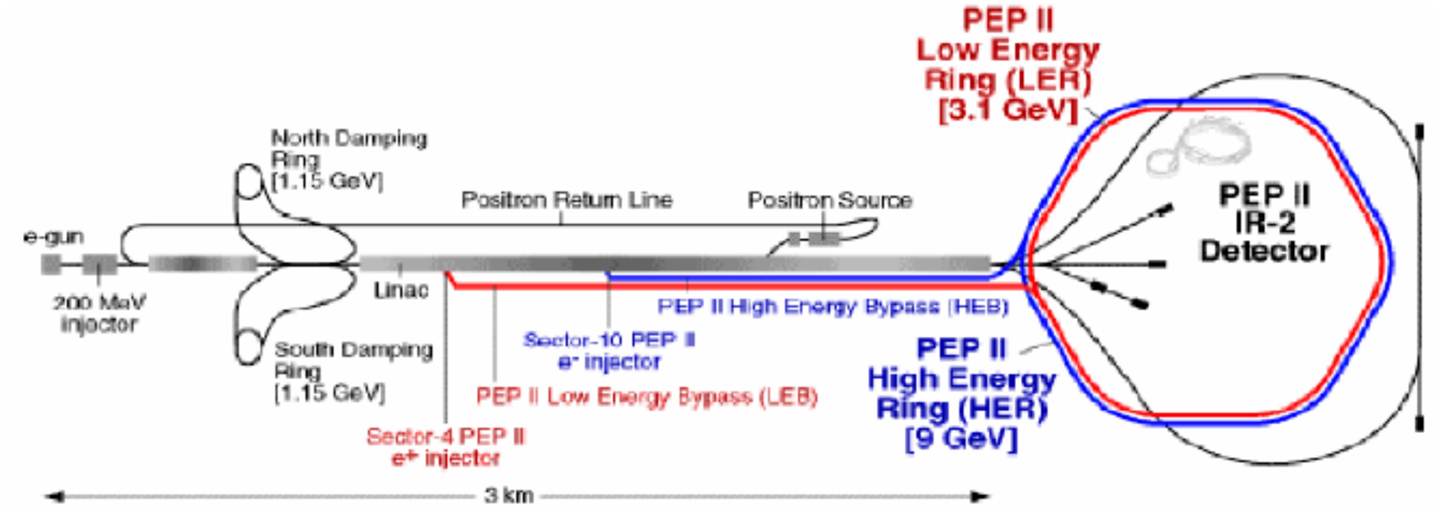


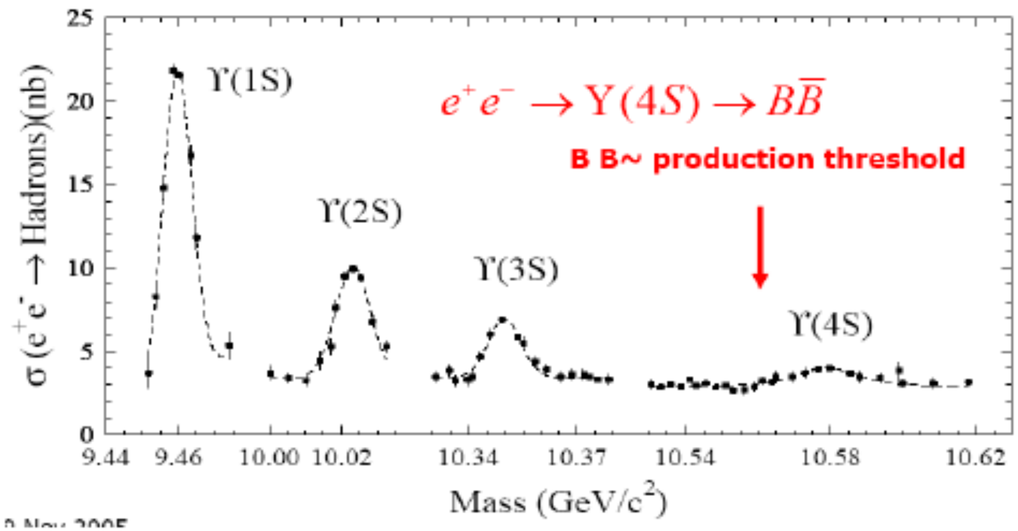


$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B^0} \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$

Problem: how do we distinguish B^0 from $\bar{B}^0$?

PEP-II Asymmetric B-Factory at SLAC





- 9 GeV e^- on 3.1 GeV e^+
- Υ(4S) boost in lab frame
  - $\beta\gamma = 0.55$

Quantum entanglement in Υ(4S)→$B^0\bar{B}^0$ decays

$$\Upsilon(4s) \rightarrow B^0 \bar{B}^0$$

With $L = 1$

Spin = 1 0 0

- Strong interaction: CP and flavor beauty number are conserved
  - Must have one **b** and one **anti-b** quarks in final state

$$|B^0_{\text{phys}}\overline{B}^0_{\text{phys}}\rangle = \frac{a}{\sqrt{2}}\,|B_L B_H\rangle + \frac{b}{\sqrt{2}}\,|B_H B_L\rangle$$

- Time evolution given by mass eigenstates

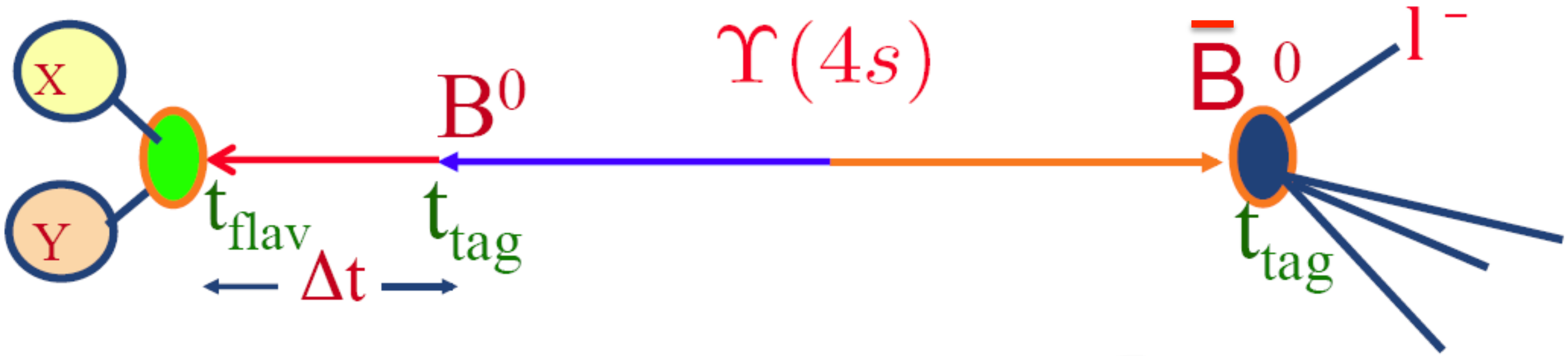
$$|B^0_{\text{phys}}\overline{B}^0_{\text{phys}}; t_1, t_2\rangle = a\,\mathrm{e}^{i\lambda_+ t_1}\mathrm{e}^{i\lambda_- t_2}|B_L B_H\rangle + b\,\mathrm{e}^{i\lambda_- t_1}\mathrm{e}^{i\lambda_+ t_2}|B_H B_L\rangle$$

- Bose-Einstein Statistics requires wave function |Ψ>to be symmetric at all times

$$|\Psi\rangle = |\Psi_{\text{flavor}}\rangle|\Psi_{\text{space}}\rangle$$

- L=-1 implies asymmetric spatial wave function
- We need a=-b which means a B^0 and a $\bar{B}^0$ meson at all times until one of them decays!
  - Example of Einstein-Podolsky-Rosen Paradox

Quantum correlation at Υ(4S)



- Decay of first B (B^0) at time t_{tag} ensures the other B is $\bar{B}^0$
  - End of Quantum entanglement ! Defines a ref. time (clock)

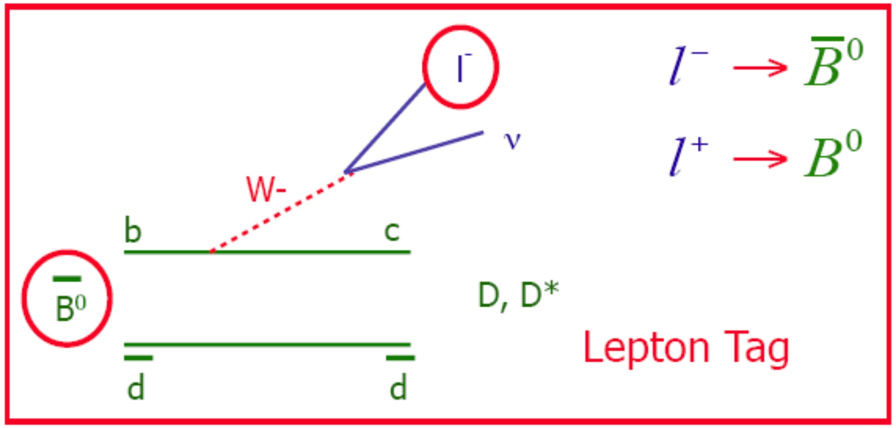
- At $t > t_{tag}$, B^0 has some probability to oscillate into $\bar{B}^0$ before it decays at time t_{flav} into a flavor specific state

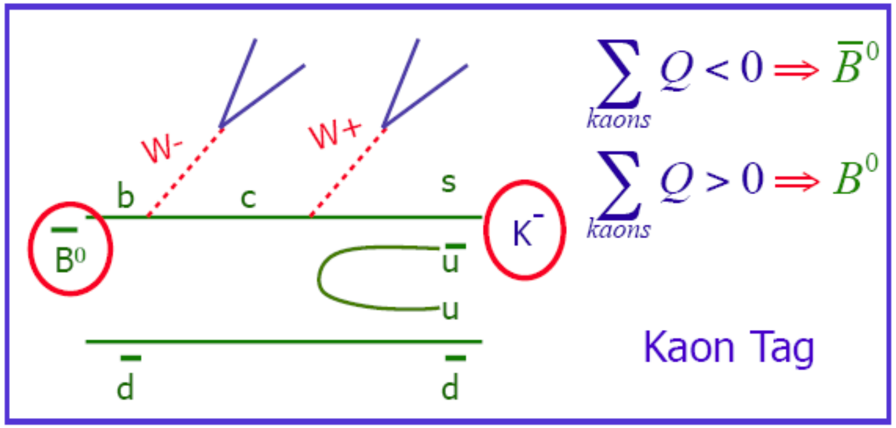
- Two possibilities in the $\Upsilon(4S)$ event depending on whether the 2nd B oscillated or not:

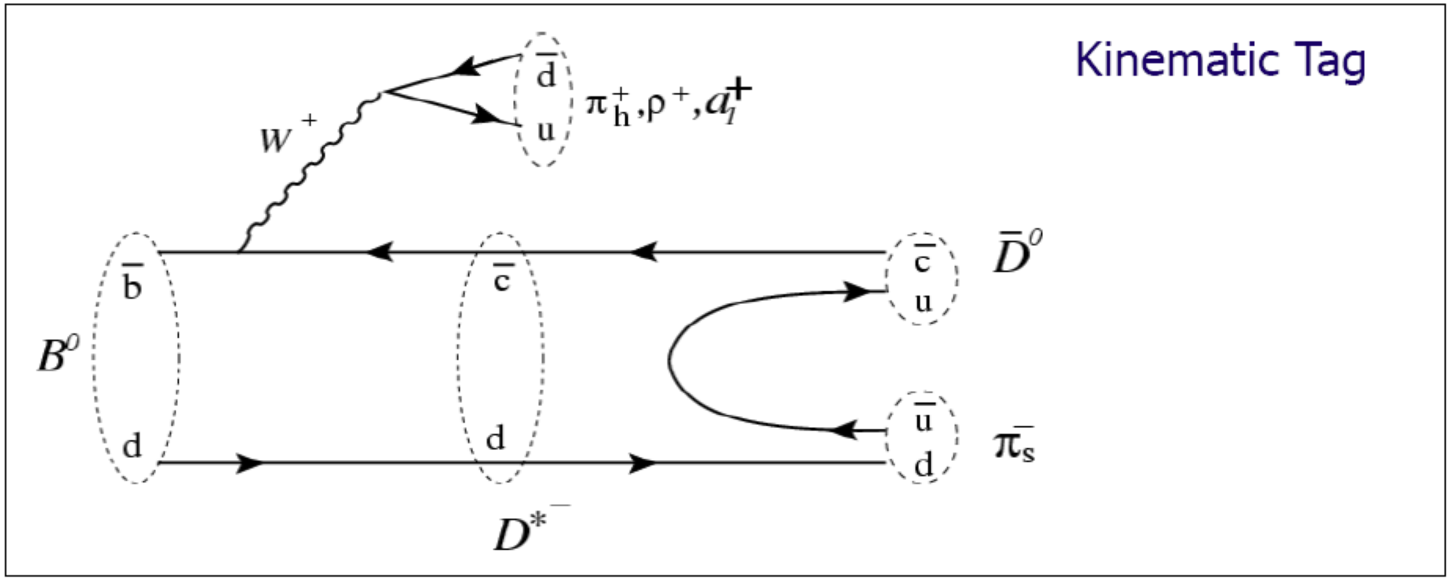
$$\text{no oscillation/mixing} \Rightarrow B^0\ \bar{B}^0 \text{ in final state}$$

$$\text{oscillation/mixing} \Rightarrow \bar{B}^0\ \bar{B}^0 \text{ in final state}$$

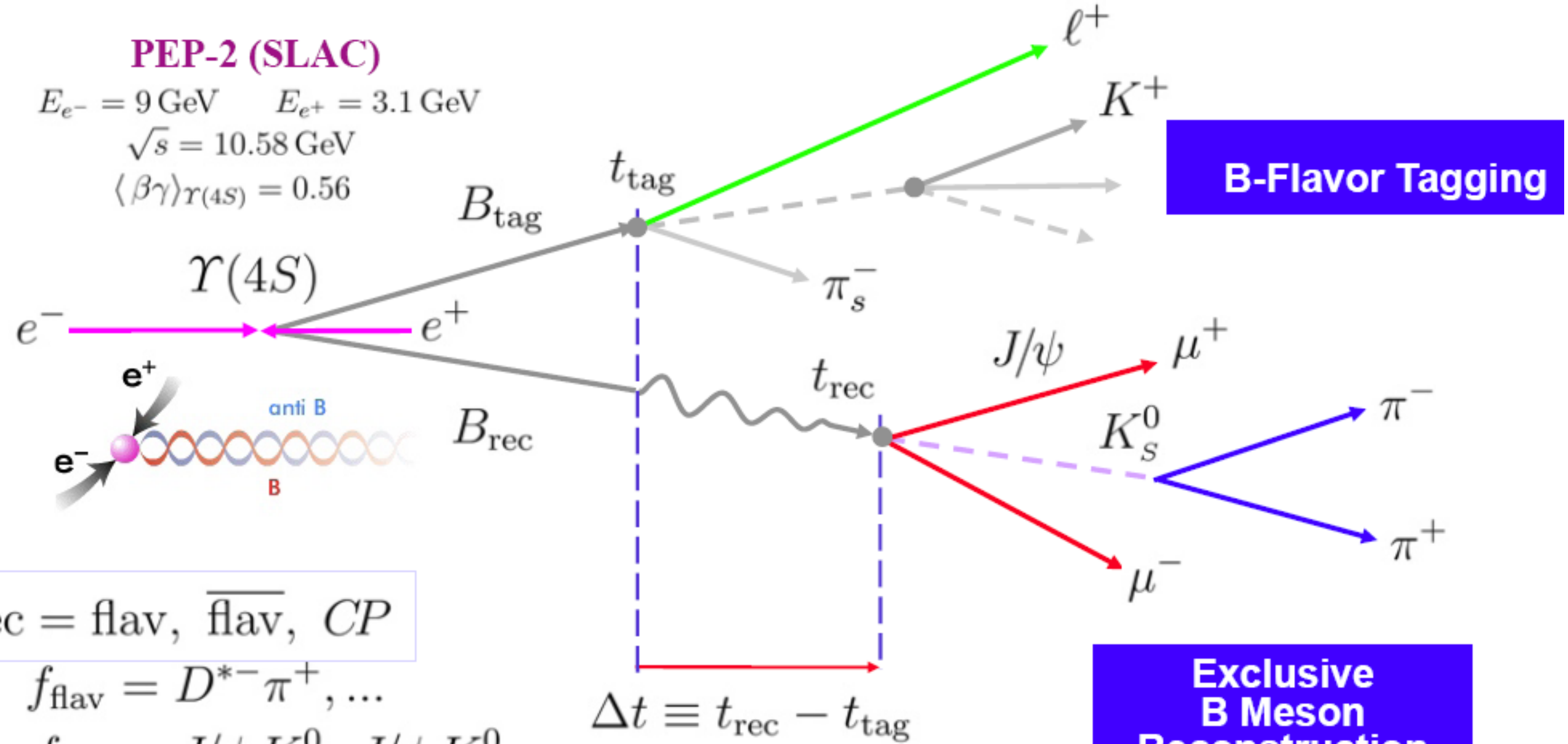
Separating B^0 and $\bar{B}^0$ mesons







Ingredients of the measurements



$$\text{rec} = \text{flav},\ \overline{\text{flav}},\ CP$$

$$f_{\text{flav}} = D^{*-}\pi^+, \ldots$$

$$f_{CP} = J/\psi\, K_S^0,\ J/\psi\, K_L^0, \ldots$$

$$\text{tag} = B^0,\ \overline{B}^0$$

$$f_{B^0} = X\ell^+\nu,\ XK^+,\ X\pi_s^-, \ldots$$

Vertexing & Time Difference Determination

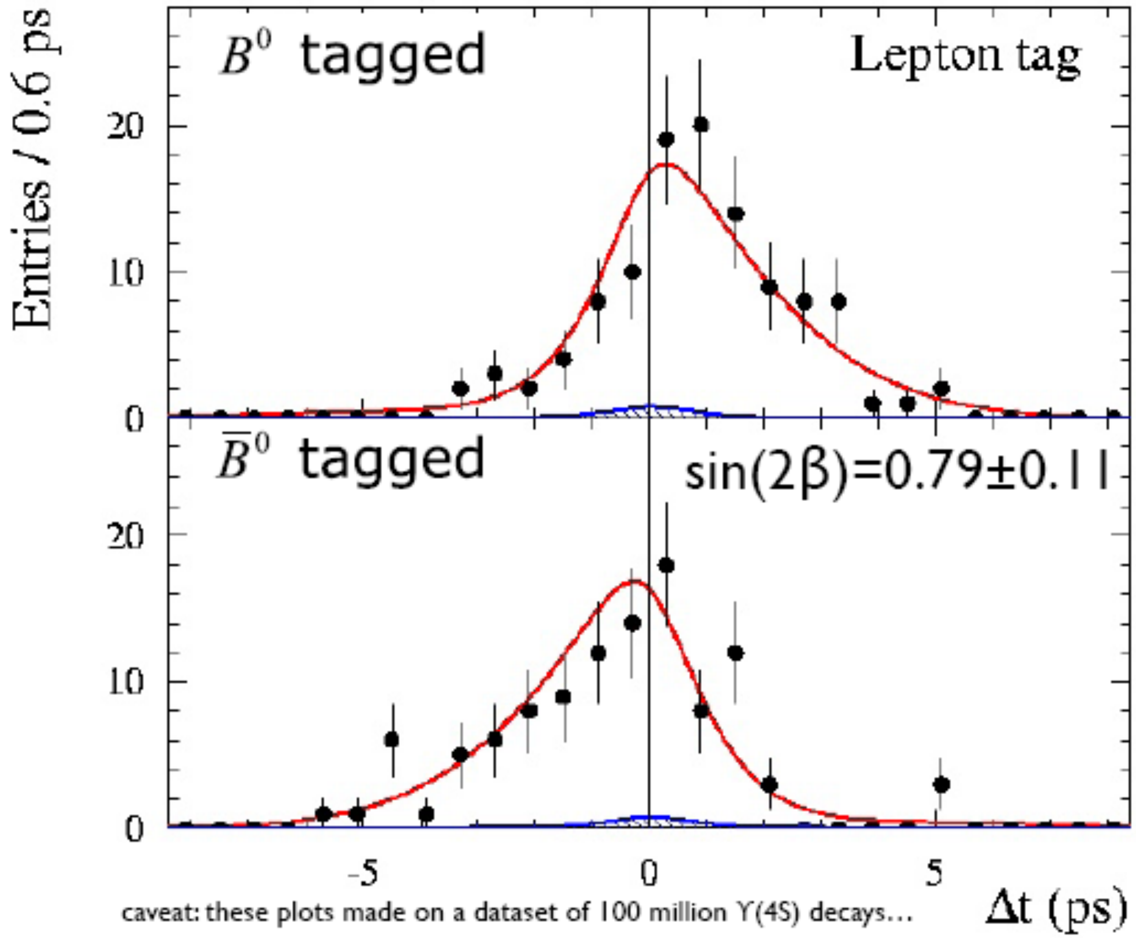
$$\Delta t \approx \Delta z / c \langle \beta\gamma \rangle_{\Upsilon(4S)}$$

$$\langle \Delta z \rangle_{B\overline{B}} \approx 260\,\mu\mathrm{m}$$

Results

CP violation in B system!

$$e^+e^- \to \Upsilon(4S) \to B_{\rm rec}B_{\rm tag} \qquad \begin{array}{rcl} B_{\rm rec} & \to & J/\psi K_S \\ B_{\rm tag} & \to & \ell^{\pm}X \end{array}$$



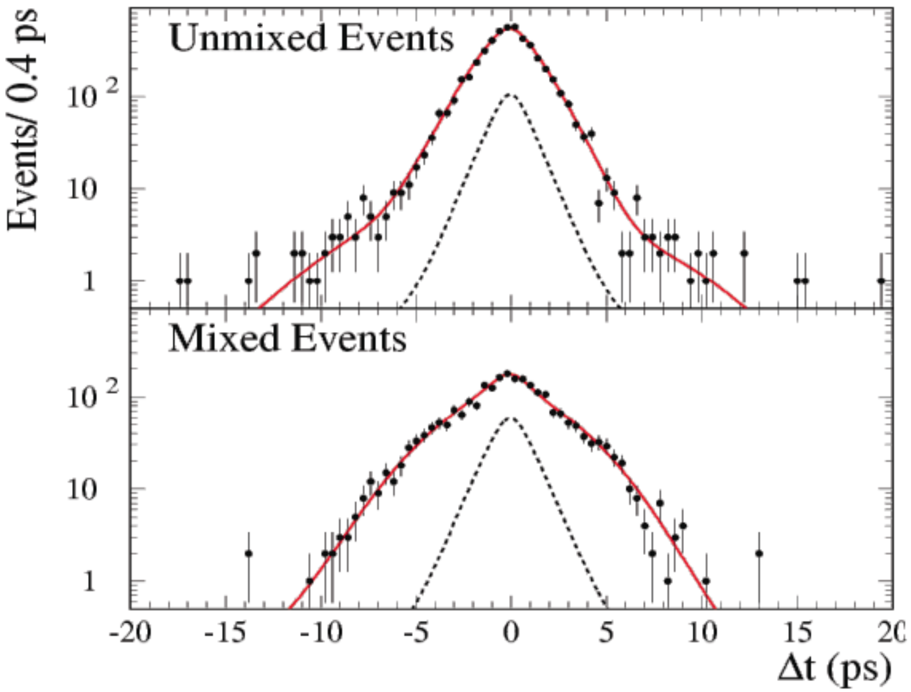
caveat: these plots made on a dataset of 100 million Υ(4S) decays…

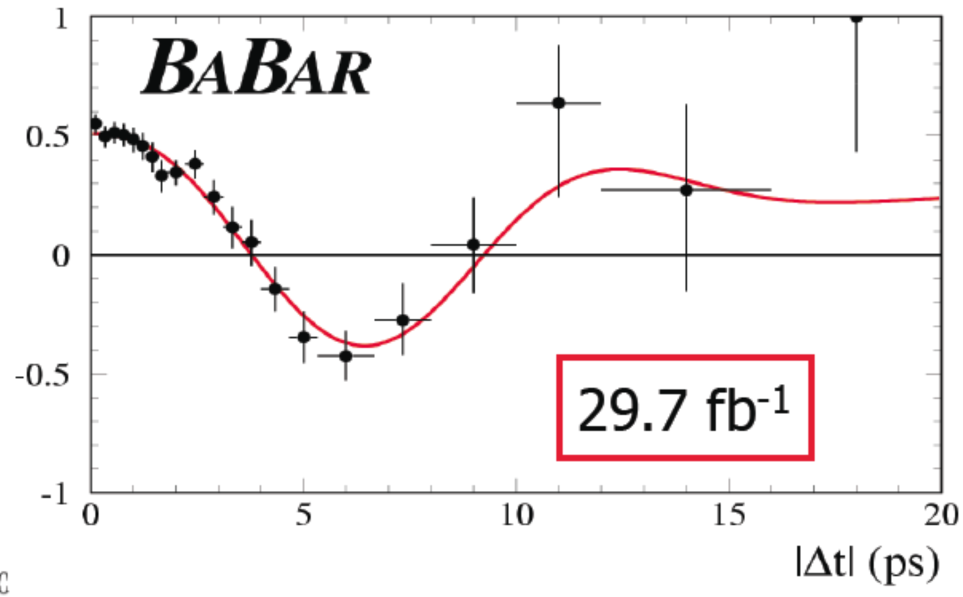
220 events

98% signal purity!
3.3% mistag rate!
20% better Δt resolution!

$B^0\bar{B}^0$ mixing: fit result

$$Asym(\Delta t) = \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)} \sim (1 - 2\langle w \rangle) \times \cos(\Delta m_d \Delta t)$$



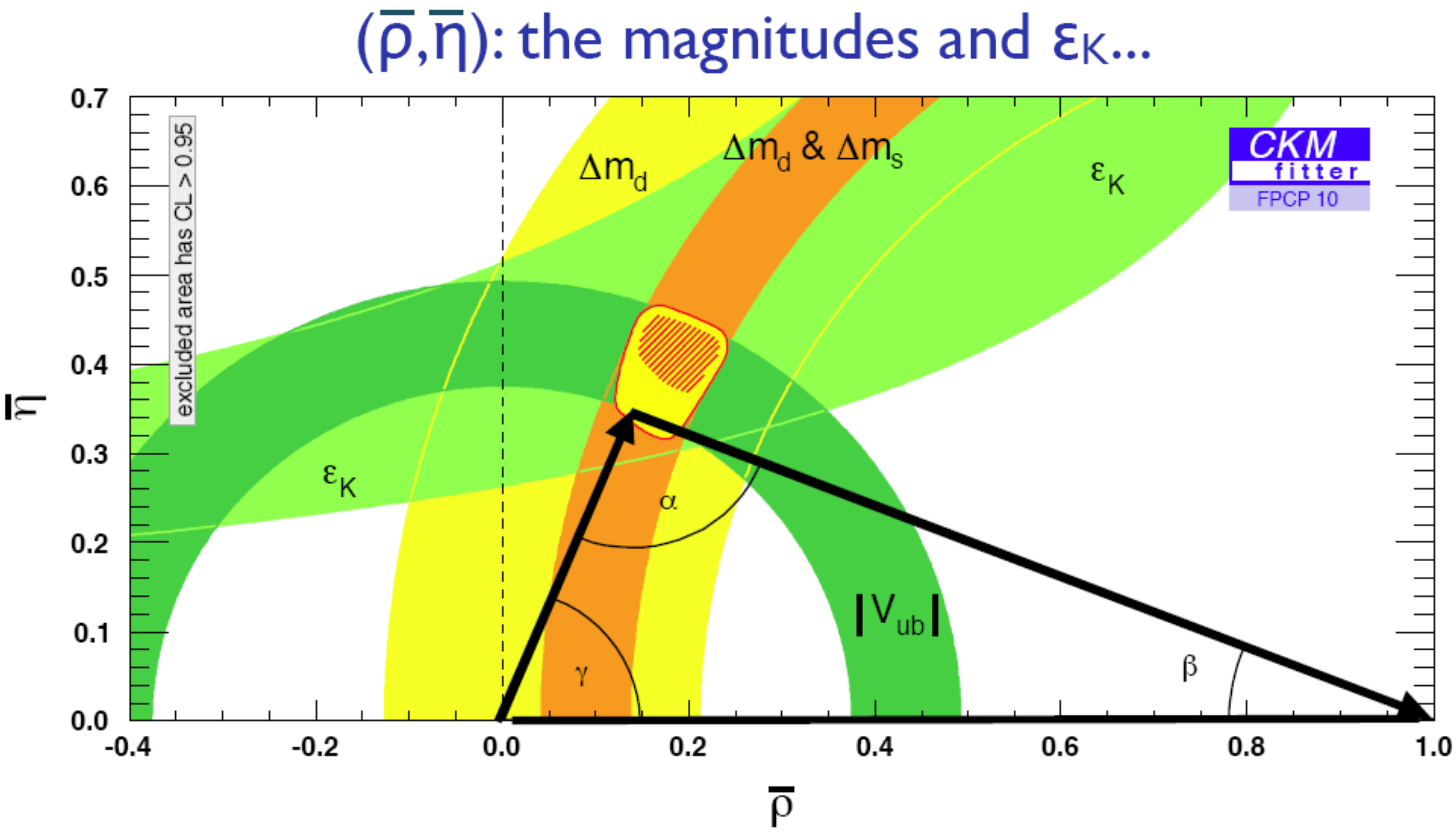


$\Delta m_d = 0.516 \pm 0.016$ (stat) $\pm$ 0.010 (syst) ps^{-1}

hep-ex/0112044
Published in PRL

Global fit to unitarity triangle

Several independent measurements, including some ones about K^0 system, are consistent with the "same" vertex of the triangle → no hints of new physics beyond SM



Direct CP violation

$$B.R.\left(B^0 \to f\right) \neq B.R.\left(\bar{B}^0 \to \bar{f}\right)$$

- If the decay amplitudes contains a phase that changes sign under CP transformation, then:

$$A = |A| e^{i\phi} \overset{CP}{\longrightarrow} \bar{A} = |A| e^{-i\phi}$$

- but this is not sufficient to have CP violation because:

$$A^* A = |A| e^{-i\phi} |A| e^{i\phi} = \bar{A}^* \bar{A} = |A| e^{i\phi} |A| e^{-i\phi} = |A|^2$$

- In order to have CP violation we must have:
  a) two amplitudes;
  b) two phases (weak phase, strong phase);
  c) only one phase change sign under CP (weak phase).

$$A = A_1 + A_2 = |A_1| e^{i\phi_W} e^{i\phi_s} + |A_2| \qquad \bar{A} = \bar{A}_1 + \bar{A}_2 = |A_1| e^{-i\phi_W} e^{i\phi_s} + |A_2|$$

$$A^* A = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\phi_s + \phi_W)$$

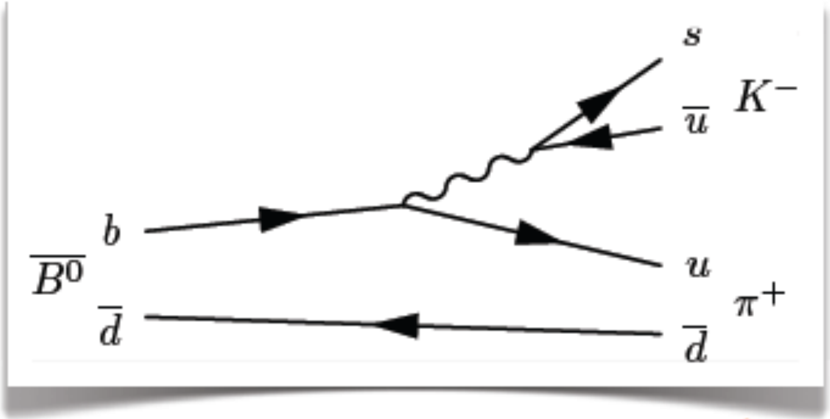
$$\bar{A}^* \bar{A} = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\phi_s - \phi_W)$$

The Γ of the two processes depend on the phases, that are different

Direct CP violation: $\Gamma(B^0 \rightarrow f) \neq \Gamma(\overline{B}^0 \rightarrow \overline{f})$

needs (at least!) 2 interfering amplitudes

Amplitude 1



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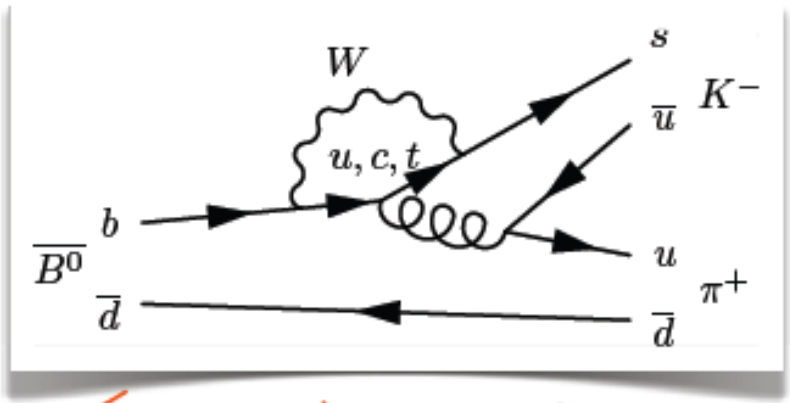
Amplitudes 2,3 and 4...



$$A_{\overline{B^0} \rightarrow K^- \pi^+} = V_{ub} V_{us}^* (T + P_u - P_t) + V_{cb} V_{cs}^* (P_c - P_t)$$

$= \mathcal{O}(\lambda^4)$ relative phase: γ $= \mathcal{O}(\lambda^2)$

Now the otherwise dominant tree diagram is suppressed by λ^2!

potentially ~equal amplitudes with *both* different strong and weak phases !

→ $\Gamma(B^0 \rightarrow f) \neq \Gamma(B^0 \rightarrow \overline{f})$

Observation of direct CP V. in $B^0 \rightarrow K^-\pi^+$

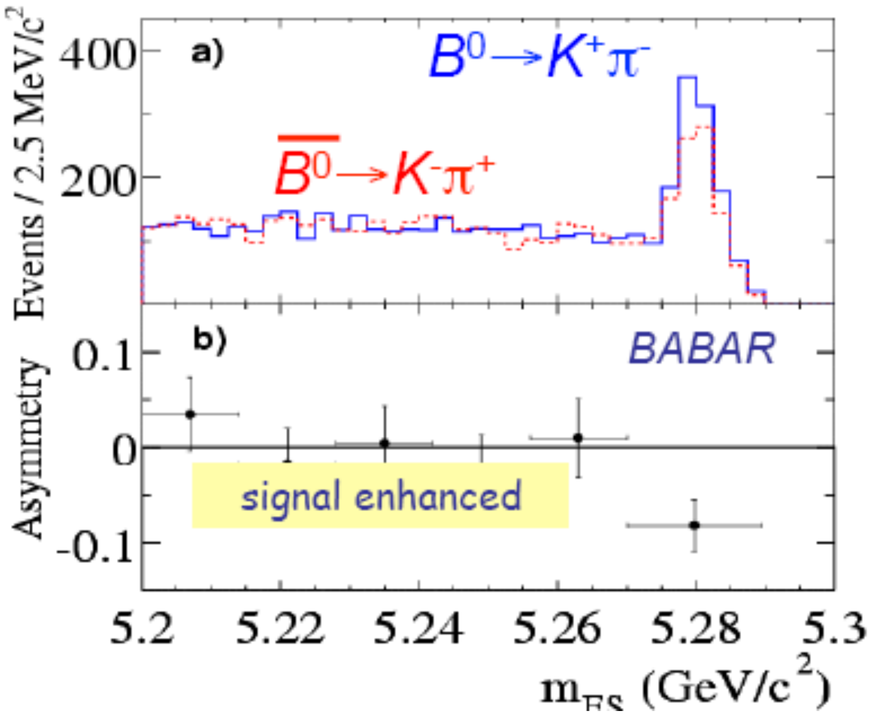
$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \rightarrow K^-\pi^+) - \Gamma(B \rightarrow K^+\pi^-)}{\Gamma(\overline{B} \rightarrow K^-\pi^+) + \Gamma(B \rightarrow K^+\pi^-)}$$

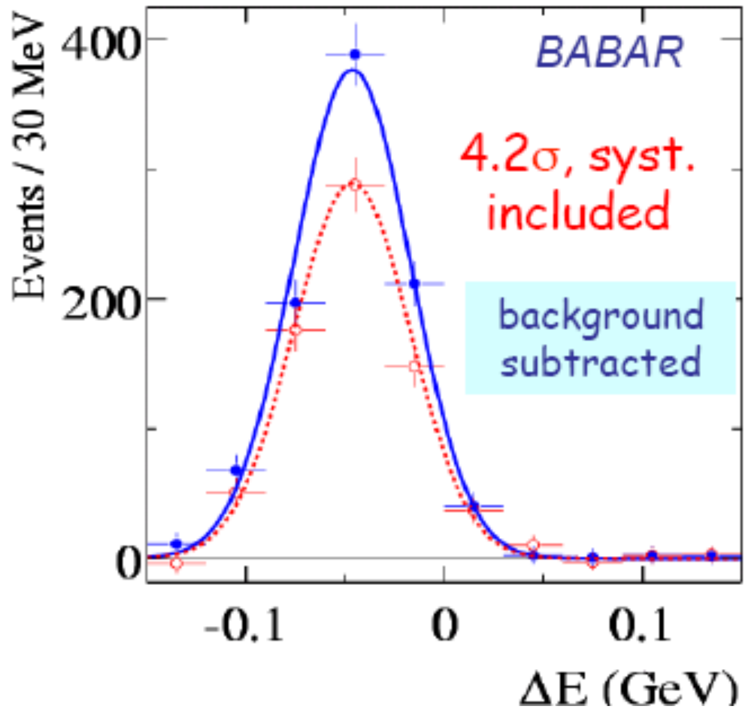
$$n_{K\pi} = 1606 \pm 51$$

$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

$$n\left(B^0 \rightarrow K^+\pi^-\right) = 910$$

$$n\left(\overline{B}^0 \rightarrow K^-\pi^+\right) = 696$$





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End of chapter 9